Acoustics of Porous Media Including Marine Sediments

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LONG-TERM GOALS

The purpose of the research is to develop a unified theory of wave propagation in granular materials, both unconsolidated and consolidated. In the context of marine sediments, the unconsolidated materials include sands, silts and clays; and examples of consolidated media are sedimentary rocks such as sandstone and limestone. The theory is to be based on well-defined physical mechanisms. It must account for the properties of the compressional, shear, and interface waves; it must be internally consistent; and its predictions, particularly concerning attenuation and dispersion, must agree with available experimental data.

SCIENTIFIC OBJECTIVES

In unconsolidated marine sediments, the frequency dependence of the attenuation and the related issue of the dispersion of the compressional (P) and shear (S) waves are still uncertain. A growing body of evidence suggests, however, that at higher frequencies, above about 5 kHz, the attenuation of the P-wave scales as the first power of frequency, f. A similar conclusion, over a more restricted frequency range, holds for the S-wave. It is widely recognized that such behavior is not consistent with Biot's theory of wave propagation in poro-elastic media. The primary dissipation mechanism in the Biot theory is viscosity of the pore fluid, which yields an attenuation that scales as f^2 below some threshold frequency, converting to $f^{1/2}$ above.

In the current research, a new mechanism is introduced based on the stress relaxation that occurs at grain boundaries during the passage of a wave. The objective is to develop a new theory of wave propagation based on the grain-to-grain stress-relaxation mechanism. The predicted frequency dependence of the attenuation, along with the theoretical dispersion, are to be compared with available data. The causal links between the wave properties are also to be explored. Predictions of wave properties are to be attempted, with a view to obtaining high-precision agreement with data. The dependence of wave properties on porosity and grain size is to be included in the theoretical development.

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APPROACH

The analysis of the stress relaxation that occurs at grain boundaries during the passage of a wave must take account of the physics of grain-to-grain interactions. In saturated (and possibly also in air-dry) granular materials, a “contact” between two grains does not actually consist of two mineral particles touching, but instead is a “near-contact” where the particles are separated by a very thin film of pore fluid. This pore-fluid film, only a few molecular diameters thick, is likely to have properties, notably the viscosity, which are quite different from those of the bulk fluid. It is known from the tribology literature that a very thin aqueous fluid film does not become significantly thinner under increasing compression, and that as the compressive force rises, the effective viscosity increases dramatically. This suggests that during the passage of a wave, which subjects a grain “contact” to a time-dependent strain, the effective viscosity of the fluid between the grains is itself time-dependent.

Such a time-dependence in a physical “constant” may be very important to the understanding of wave propagation in saturated granular media. The effect of the time varying viscosity has been incorporated explicitly into the stress-relaxation term in the Navier-Stokes equation for the medium. From this equation, two wave equations have been derived, one for compressional and the other for shear disturbances. These equations yield simple algebraic expressions for the wave speeds and attenuations. Both wave speeds are predicted to show near-logarithmic dispersion, and both theoretical attenuations scale essentially as the first power of frequency.

Only three unknown constants appear in the four expressions for the wave speeds and attenuations. These three constants may therefore be determined from just three of the expressions combined with data, and the fourth is then used to predict the value of the remaining wave property. This provides a rigorous test of the theory. Of the four wave properties, it is most convenient to predict the compressional attenuation. With the very limited data sets available, agreement with measurements of P-wave attenuation appears to be within 1 dB/m at a frequency of 38 kHz. More data sets are required in order to facilitate further testing.

WORK COMPLETED

The unified theory of wave propagation in saturated granular materials has been developed and published in four papers in the Journal of the Acoustical Society of America. The first deals with the compressional wave in unconsolidated media, the second with the shear wave, the third with the interface wave, and the fourth with the wave properties of consolidated materials. A fifth paper is due to appear shortly in J. A. S. A. on the physical mechanism underlying stress relaxation at grain boundaries. A discussion of the high-precision correlations emerging from the theory is to be published in the Journal of Computational Acoustics.

Two at-sea experiments in the Gulf of Mexico, one off Panama City and the other off Destin (SAX’99), have been performed, using a vertical line array of four elements to collect shot data from an airgun in a shallow (• 20 m) environment. The shot data have been inverted to recover the speed of the P-wave in the sediment at a frequency of approximately 70 Hz.

RESULTS

The theory is described comprehensively in the J.A.S.A. and J.C.A. papers. At higher frequencies (> 5 kHz) it yields excellent agreement with available data. However, complete data sets (P-wave and S-wave speeds and attenuations) are rare and more are needed to allow the theory to be fully tested.

The new approach to wave propagation in sediment acoustics has received widespread attention. It has been the topic of many invited presentations and several keynote lectures at international conferences on acoustics. This is the first time that the behavior of molecularly-thin fluid films has been proposed as an important mechanism in granular materials. This may turn out to be a fascinating area of future experimental and theoretical research.

IMPACT/APPLICATIONS

The new approach to wave propagation in sediments is important for all underwater acoustic propagation modeling, especially in shallow water, where bottom interactions are significant. It is also relevant to shallow-water ambient noise modeling. In addition, the theory can be used as the basis of various inversion techniques, for instance, matched field, for estimating the geoacoustic properties of the bottom from measurements of the sound field in the water column. The strong correlations between certain wave properties identified in the theory could be applied with advantage to reduce the number of unknown parameters appearing in inversion schemes.

TRANSITIONS

Since the theory is still under development, it is really too early to consider transitioning. However, one group, headed by Dr. K. A. Naugolnykh, CIRES, University of Colorado/NOAA, Environmental Technology Laboratory, Boulder, Colorado, has applied the theoretical ideas to the case of non-linear, laser-generated sound pulses in a granular medium. They found that the theory agreed very satisfactorily with their results.

RELATED PROJECTS

U.S.A.

1. Dr. Michael Richardson, N.R.L., Stennis, and I are collaborating on the interpretation of sediment wave property data obtained using his ISSAMS frame.

United Kingdom

1. Dr. Sam Marks, Defence Evaluation and Research Agency (DERA), Winfrith, holds an extensive data set of sediment properties from world-wide locations. We are currently exploring ways of using these data to help in the theoretical development.

2. Dr. Gary Heald, DERA, Winfrith and Dr. Nicholas Pace, University of Bath (currently at SACLANTCEN, La Spezia, Italy) are collaborating with me in developing laboratory and in situ experiments aimed at determining sediment wave properties, particularly P-wave dispersion, from measurements of the reflection coefficient of the seafloor.

France

1. Dr. Jean-Pierre Sessarego, Laboratoire de Mecanique et d’Acoustique, C.N.R.S., Marseille, has a laboratory-based experimental program on acoustic waves in sediments. We are currently planning a cooperative effort with this laboratory aimed at testing, under controlled conditions, some of the predictions of the new theory.

PUBLICATIONS

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8. M.J. Buckingham, "Precision correlations between the geoacoustic parameters of an unconsolidated, sandy marine sediment," *J. Comp. Acoust.*, **in press** (2000). INVITED.

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